UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION / AVAILABILITY OF REPORT A Statement. Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) NWC TP 6841	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Weapons Center 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) China Lake, CA 93555-6001	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING / SPONSORING ORGANIZATION Naval Weapons Center 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code) China Lake, CA 93555-6001	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
64710N	R0371	R0371	

11. TITLE (Include Security Classification)

STRUCTURAL INTERPRETATION OF THE COSO GEOTHERMAL FIELD

12. PERSONAL AUTHOR(S)
Austin, C. F.; and Moore, J. L.

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15 PAGE COUNT
Summary	FROM Oct 86 TO Aug 87	1987 September	34

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Geology of Southern Sierra Nevada, Coso geothermal area, reservoir analysis
08	07		
08	02		

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The Coso Geothermal Field, located east of the Sierra Nevada at the northern edge of the high Mojave Desert in Southern California, is an excellent example of a structurally controlled geothermal resource.

The geothermal system appears to be associated with at least one dominant north-south trending feature that extends several miles through the east-central portion of the Coso volcanic field. Production from wells drilled along this feature is attributable to distinct fractures in crystalline basement rocks. The identified producing fractures occur in zones that range from tens to hundreds of feet in extent, separated by regions of essentially unfractured rock of similar composition.

Proposed origins of the zones of vertical fracturing are quite diverse and provide additional fuel for the continuing debate concerning structural control. Theories that invoke both extensional and compressional tectonic settings, include a system of individual breccia pipes, networks of intersecting through-going faults and fracturing associated with dome emplacement, and localized zones of extensive hydraulic fracturing.

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED	
22a. NAME OF RESPONSIBLE INDIVIDUAL C. F. Austin	22b. TELEPHONE (Include Area Code) (619) 939-3411/x228	22c. OFFICE SYMBOL Code 266

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

(continued from 19)

Wells in the Devils Kitchen area have encountered fluids in excess of 450°F and flow rates of one million pounds per hour (pph) at depths of less than 4000 feet. A step-out exploration/production well drilled in 1986 to a depth of 6553 feet, located several miles south of the Devils Kitchen region along the identified north-south feature, produced fluids with a temperature greater than 640°F.

While the extent of the resource is not yet known, reservoir tests to date estimate 240 megawatts (MW) of power will be available from the Coso field. Construction of the first 25-MW power plant began in the first part of 1986. This construction is complete and the station is on line.

NWC TP 6841

Structural Interpretation of The Coso Geothermal Field

by
C. F. Austin
Public Works Department
Naval Weapons Center

and

J. L. Moore
California Energy Company, Inc.
Santa Rosa, California

SEPTEMBER 1987

NAVAL WEAPONS CENTER
CHINA LAKE, CA 93555-6001

Naval Weapons Center

FOREWORD

This report documents a study funded by the Coso Geothermal Development Program under task number R0371 during fiscal year 1987. This report was originally presented as an invited paper at the Energy and Minerals Session of the 1987 National Meeting of the American Association of Petroleum Geologists in Los Angeles, Calif. The work involves interpretive modeling of the Coso region of the southern Sierra Nevada and vicinity.

The report has been reviewed for technical accuracy by Dr. James Whelan.

Approved by
K. C. KELLEY
Capt., CEC, USN
Public Works Officer
24 September 1987

Under authority of
J. A. BURT
Capt., USN
Commander

Released for publication by
G. R. SCHIEFER
Technical Director

NWC Technical Publication 6841

Published by .... Technical Information Department
Collation .... Cover, 18 leaves
First Printing .... 140 copies

CONTENTS

INTRODUCTION

The interpretation of the geology of the Western United States is in a great state of flux. This situation is leading to the demise of many cherished and long-held concepts and to the uncertainty and excitement of finding new interpretive treasures in what has been considered by many to be a totally explored and understood conceptual arena. This modern pulse of change was called out most clearly in recent times by David R. Lageson of Montana State University in "Regional Tectonics of the Cordilleran Fold and Thrust Belt" (1982 AAPG Fall Education Conference), in which he stated:

> "A regional tectonic synthesis of the North American Cordillera is currently being pieced together through paleomagnetic and stratigraphic data coupled with new plate tectonic concepts and kinematic models. Text books are literally being rewritten on the tectonic geology of western North America based on the micro-plate or exotic terrane theory of continental accretion."

We believe that we too are contributing to the growing understanding of the geology of western North America, and to a rekindling of the need for people to look again at the data that pertain to the southern Sierra Nevada and vicinity. We urge that people emulate us by trying to dig out and examine the uninterpreted raw data, then to see how many new and different ways the data can actually be interpreted. New interpretations of the data are most apt to lead the explorationist to the hidden anomalies that we call mineral deposits.

The information given in this report was presented on 6 June 1987 in Los Angeles, Calif. as an invited paper at the Energy and Minerals Session of the 1987 National Meeting of the American Association of Petroleum Geologists. The sequence of the figures in this paper is the same as that of the slides shown in the original presentation. We hasten to state that we do not expect our interpretations to stand unchanged for all time. Rather we believe our interpretive model to be the best fit for the data in hand today. Certainly this model will present a challenge to traditionalists and explorationists alike to examine every facet of the data once again to see if we have stumbled or if we have truly opened a new vista for all to exploit. In particular, we hope our interpretations, as expressed in this paper, excite people to reexamine the Sierra Nevada and the southwestern Basin and Range province, to seek new data, and to find new theories, whether complementary or opposing. We hope our interpertations will encourage people to enter wholeheartedly into discussions and efforts to better understand this surprisingly little-studied and poorly understood region of great geologic complexity.

Recently we were delighted by an example of what we hoped to accomplish, at a presentation of some of the major concepts of this paper at a regional conference of geology teachers. A senior college professor in the audience stated that our ideas had opened up an entire vista he had never considered and that he would have to immediately reread many of the past studies we had cited. We consider our paper to be a clear-cut success when we can engender such a response.

We would remind all of our readers that our model for the Coso region is based on fundamental concepts and data that are not novel to those who are students of the history of geology as a science, especially as this geology pertains to our specific geographic area of study. The debates of regional compression (folding and thrusting) in the Basin and Range versus regional extension (grabens and horsts) have been with us for many generations. We have simply taken the data package for the Coso geothermal area and surrounding region as we understand it today, and have made what we think is the most logical and best fitting model for ourselves and others to test.

In the 1870s proponents of the battle of tension versus compression for this region formed sides. Clarence King, writing initially in the *Atlantic Monthly* and the *Overland Monthly* in 1871 and then in *Mountaineering in the Sierra Nevada* (now available through the University of Nebraska Press), stated regarding the Sierra Nevada Region:

> "In the late Tertiary period a chapter of very remarkable events occurred. For a second time the evenly laid beds of the sea-bottom were crumpled by the shrinking earth . . . ."

Within 3 years, this concept of compression during the late Tertiary in the general sierran region was countered by Gilbert's classic extensional model for the Basin and Range, published in 1874. Although Spur (1901) raised some doubts over Gilbert's concepts, Baker (1913) was the one who truly rekindled the thrusting model for the southwestern Basin and Range. As time progressed more and more investigations of the Basin and Range concerned the geometric improbability, if not outright impossibility, of mountain building through extension. Davis (1925) raised the very same questions the COCORP (1987) by Allmendinger study attempted to address. Davis was followed by Willis (1934) and Lawson (1936), both of whom described the east front of the Sierra as a thrust fault. Nolan (1943) raised virtually the same issues of fault geometry, whereas Mayo (1941), in his mapping of the faults of the Sierra Nevada front, addressed the complex nature of the eastern front of the Sierra and noted once again that most of the faults he observed were reverse faults.

We hope the readers will carefully consider not philosophic dogma, but data and field evidence. We also hope that only after this careful consideration, will they seek to choose theoretical and genetic concepts that apply.

As a final anecdote, after one recent presentation of our concepts, a member of the audience excitedly discussed with us how our ideas of compression would fit with a spreading-center concept that he was proposing for the mid-Basin and Range and how his concept would substantiate thrusting in the area that we discussed. The possibilities for new combinations of ideas and models and, as a result, discovering the location of new mineral resources, and the recognizing of new avenues of study to pursue are what make geology a dynamic and exciting field of study. You may not like our model. If you do not, we challenge you to take the actual data and find a better one.

AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS (AAPG) NATIONAL MEETING PRESENTATION

In 1979, the United States Navy, at the Naval Weapons Center (NWC), China Lake, Calif., undertook a new and unique project. This project was to contract for the exploration and development of a portion of the Coso geothermal system, with private industry using private-sector capital, i.e., no capital cost to the Navy. The California Energy Company as the Navy's contractor discovered a superb resource. Together we, California Energy, and the Geothermal Program Office of NWC have learned some startling and exciting geology along the way.

OBJECTIVES

The primary objectives of this paper are to present

1. The results of exploration along the eastern edge of the southern Sierra Nevada.

2. Some alternate interpretations of structures of the southern Sierra Nevada and adjacent Basin and Range that seem consistent with all of our geological findings.

3. Economic implications of the alternate structural interpretations that have resulted from the successful exploration of Coso geothermal system.

COSO GEOTHERMAL SYSTEM

Our general area of interest is the southeastern Sierra Nevada and the ranges immediately to the east as shown in Figure 1. Over the past several decades, the Sierra has been referred to as the western-most range of the Basin and Range both as to position and structure. However, with the burgeoning evidence for pervasive low-angle faulting throughout the Basin and Range, characterized by some as a region of asymmetric 1/2 grabens, plus the increasing recognition by active field workers of low-angle faulting within the Sierra itself and the resulting rather obvious conclusion of probable detachment of the Sierra Nevada, no longer can we arbitrarily draw a meaningful tectonic boundary at the eastern edge of the Sierra. Instead, we believe the whole region must now be considered as an integral part of the entire Basin and Range complex, which would then extend from at least the overthrust belts on the east to the western edge of the Sierra Nevada as it dips beneath the Great Valley.

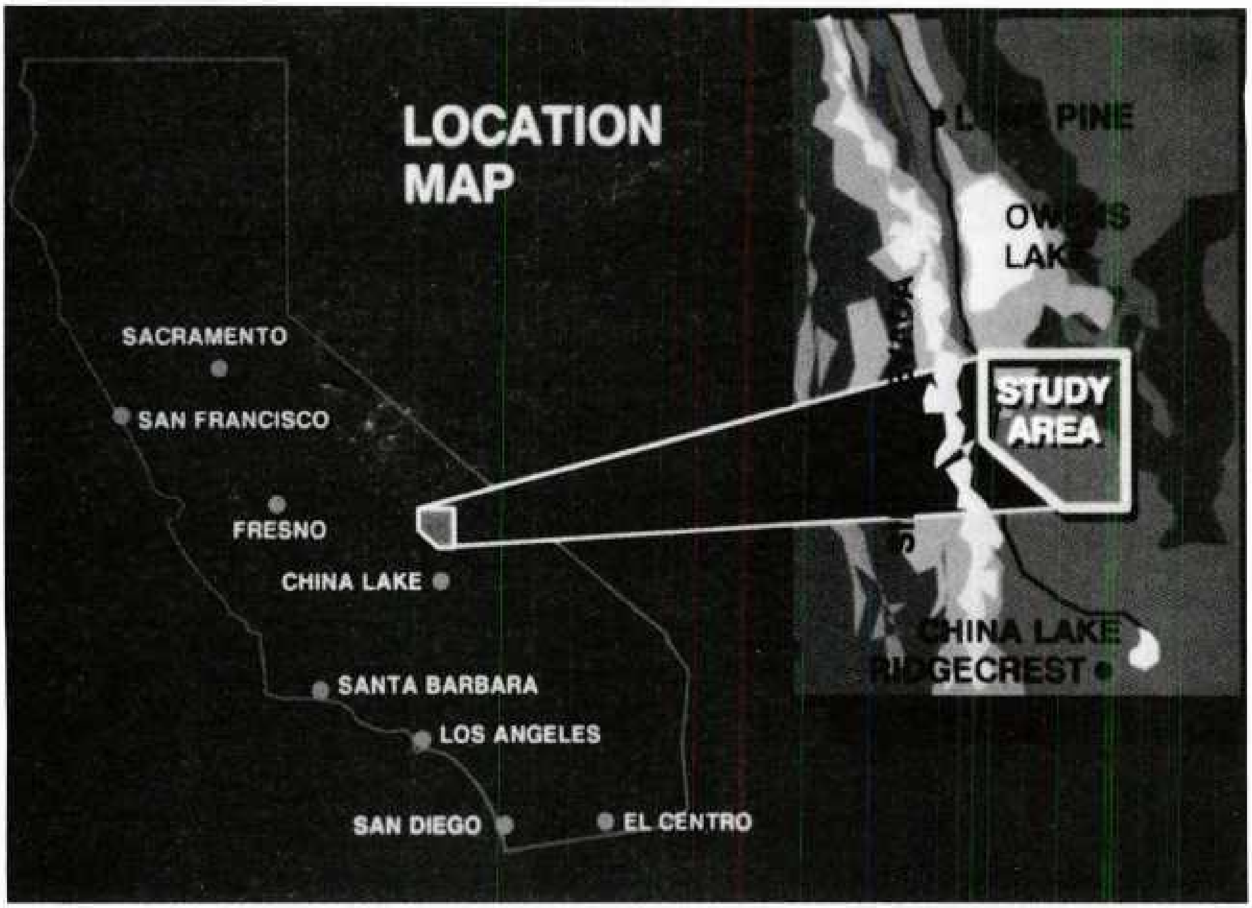


FIGURE 1. Location of Southeastern Sierra Nevada.

A fundamental question for serious study of the Coso geothermal system is whether Coso is an isolated phenomenon or simply a part of a series or swarm of similar features. The latter seems to be the case. We recognize what we think should be considered as at least 14 geothermal prospects in the general vicinity of the Coso geothermal system (Figure 2). All of these potential prospects have surface expressions that include some of the following at each site:

1. High surface heat
2. Young volcanic rocks
3. Distinctive geochemistry or associated ore deposits
4. Arcuate fracturing

Several of these prospects have truly impressive overlying or adjacent hydrothermal alteration zones with associated epithermal precious metal prospects. Coso is not a single isolated phenomenon.

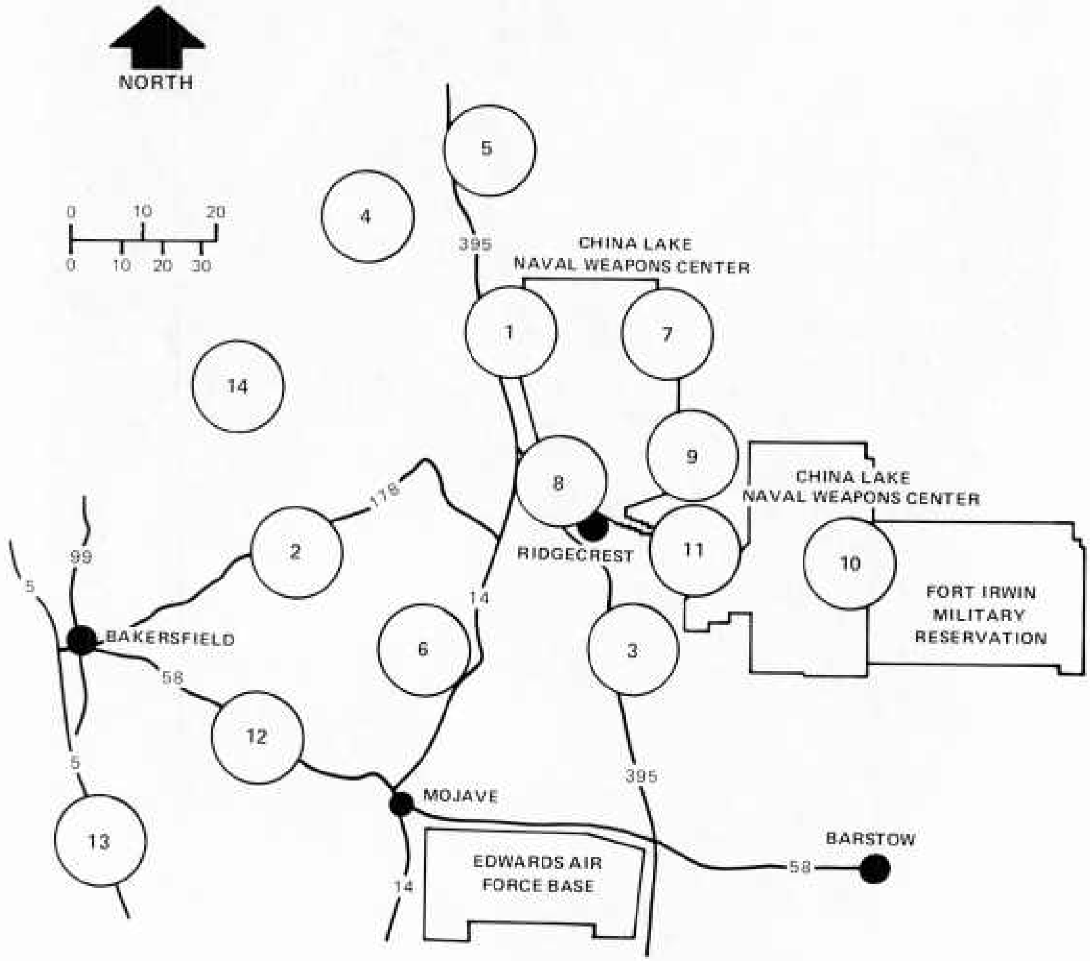


FIGURE 2. Areas of Geothermal Potential in the Vicinity of the Naval Weapons Center.

Features of the Area

Satellite views of the Coso geothermal system reveal several prominent features (Figure 3). The following list of features must be accounted for, whatever the structural model chosen.

1. Major northwest fracture zones, offsetting the Sierra front

2. A perlite dome field that is strung out in a north-south direction along the east side of a granitic ridge and that lies in what appears as a circular fracture system

3. An apparent inward-dipping fracture system, much of it arcuate, that is about 20 miles in diameter

4. A series of scallop-shaped fractures of some sort, aligned along the eastern Sierra front

FIGURE 3. Satellite View of Coso Region.

A closer look at the immediate perlite dome field shown in Figure 4 and the surrounding area shows what appears to be an upwarp of the fractured granitic basement complex through which the volcanics have erupted.

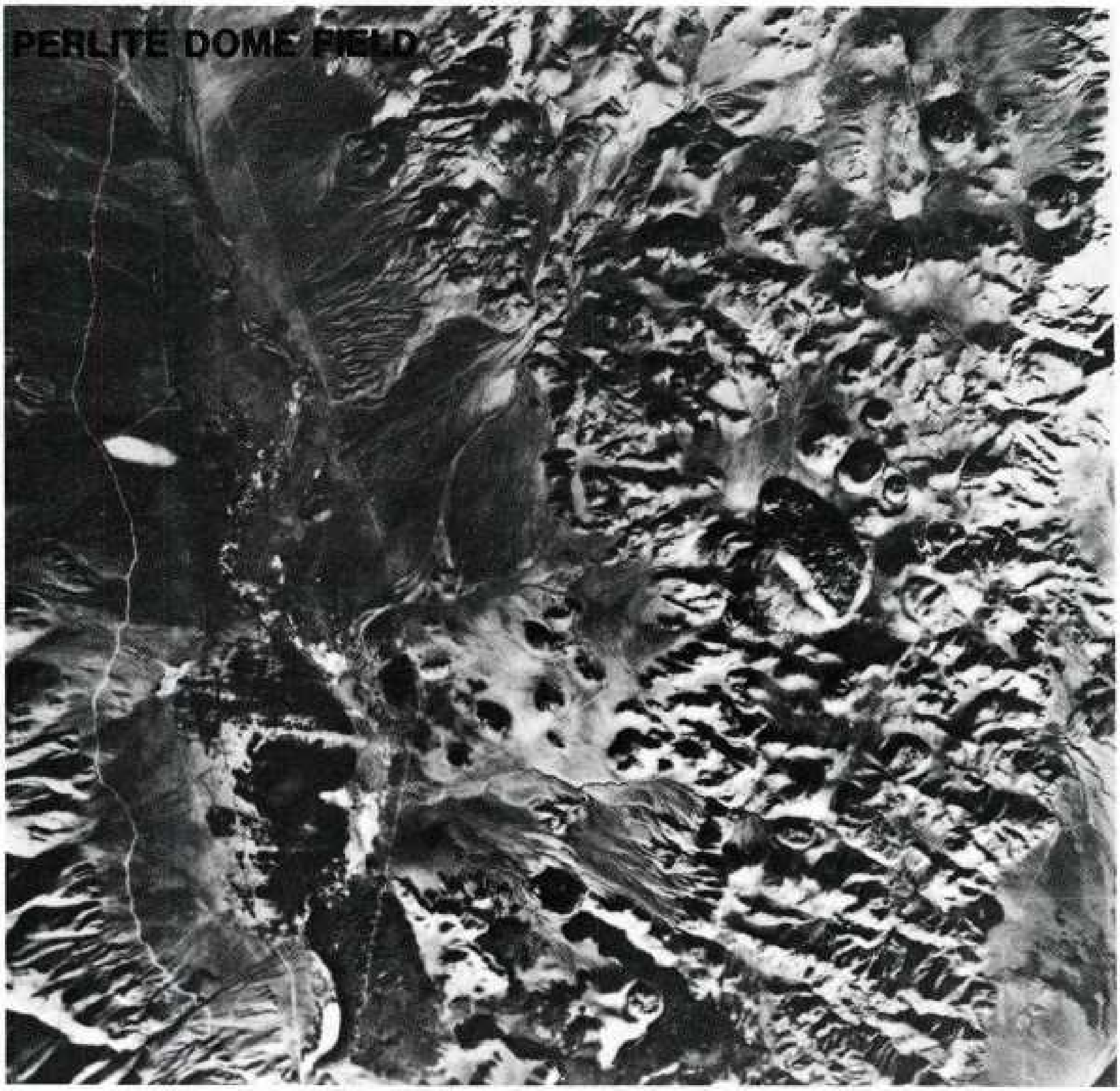


FIGURE 4. Perlite Dome Field.

In addition to the prominent perlite dome field, the Coso area has numerous small natural steam vents plus extensive steam venting from old exploration drill holes at one underground and two open-pit mercury mines. Over 42 venting old steam wells and hot water pools may be found at the former main Coso Hot Springs Resort area (Figure 5), which is located on a fault at the eastern edge of the central granitic ridge.

FIGURE 5. Red Mud Pot at Coso Hot Springs.

Exploration and Development

California Energy Company has drilled a number of successful wells such as the one shown in Figure 6. These wells range in depth from 1500 to 8000 feet and encounter a wide range of rocks and attendant alteration products. Wells in the field range up to one million pounds per hour (pph) mass flow in capacity and to over 650°F in temperature.

Following a drilling program from late 1981 to March 1986, a decision was made to construct the first power plant. This power plant (Figure 7) is a dual-flash unit, designed by Mitsubishi and erected by Guy F. Atkinson. This initial 32-megawatt plant officially went on line 15 July 1987.

With this background of successful exploration and development drilling, let us study the issues of both regional structural geology and specific reservoir geology as we see them at Coso today. We recognize quite clearly that the mortality rate for exploration models is high, but the data we have in support of our model are, in our opinion, both extensive and significant.

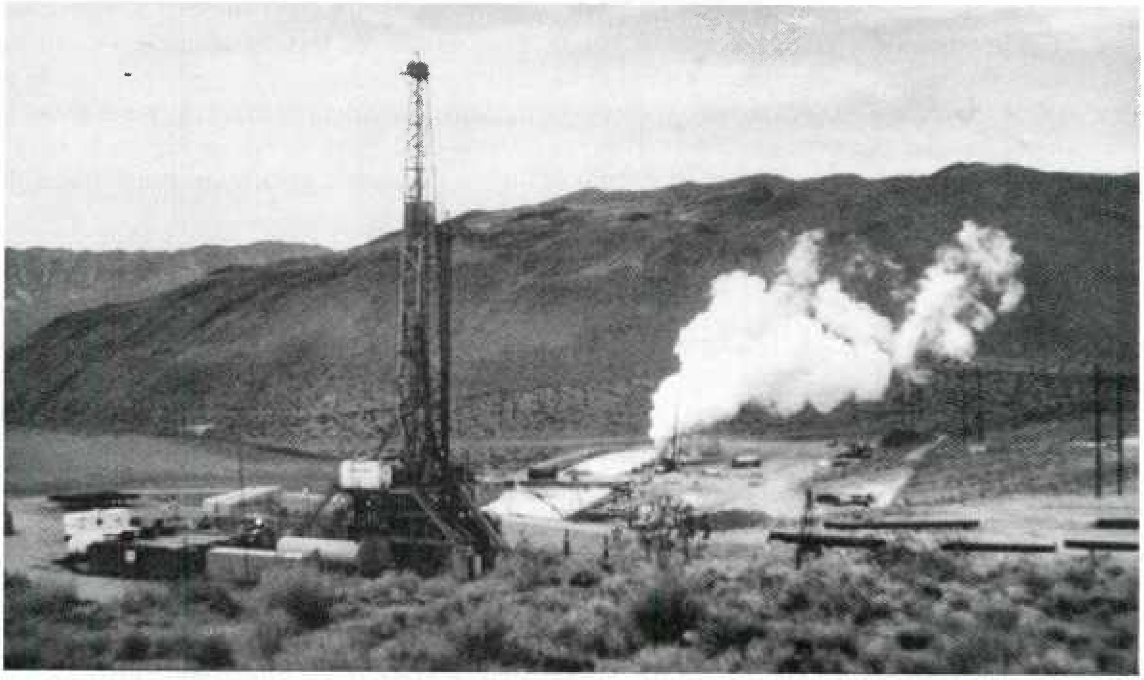


FIGURE 6. Drilling on Well No. 15A8.

FIGURE 7. Navy Geothermal Plant No. 1, Unit No. 1.

Just as an ore deposit of metals is an anomaly in the broad structural fabric of a region, so is an active geothermal system an anomaly. We must understand the broad framework or structure that hosts this anomalous feature if we are to be anything more than amateur prospectors. In the case of the Basin and Range, the arguments over fundamental structure that are raging today are not new. Consider the words of Nolan (1943) or Davis (1925), as shown in Figure 8, both of whom clearly recognized even then the improbability of the classic graben and horst model that stemmed from Gilbert's work in 1874.

STRUCTURAL SETTING:
THE UPLIFT PROBLEM IS NOT NEW

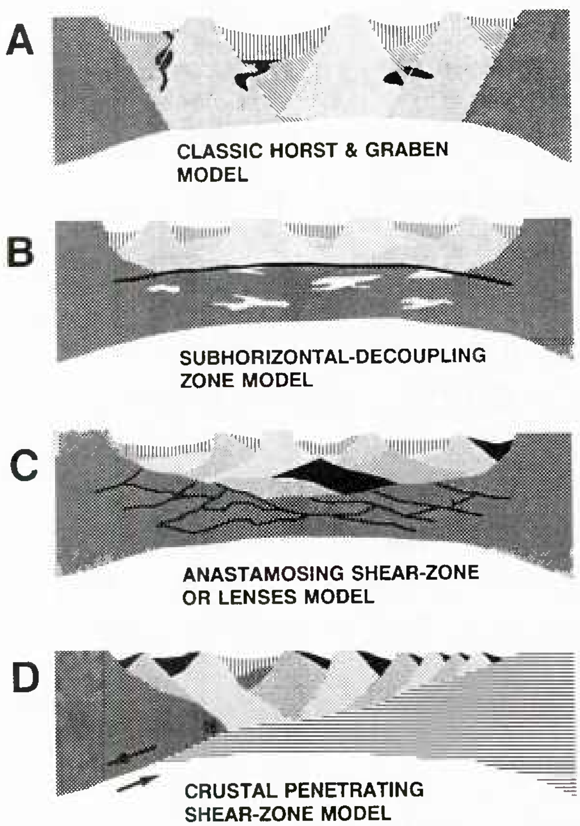
NOTES FROM "STRUCTURAL GEOLOGY OF NORTH AMERICA" BY EARDLEY (1951) ON BASIN AND RANGE

- FROM NOLAN (1943) "TILTING, THE EFFECTS OF WHICH HAVE BEEN OBSERVED IN THE REGION, APPEARS IMPOSSIBLE OF ACCOMPLISHMENT UNLESS ACCOMPANIED BY EITHER PLASTIC FLOW OR WIDESPREAD SHEARING AT RELATIVELY SLIGHT DEPTHS"
- "SHORTENING OF THE CRUST MAY BE A RESULT OF NORMAL FAULTING IF THE RADIUS OF CURVATURE OF THE FAULT PLANE IS LESS THAN WIDTH OF THE TILTED FAULT BLOCK."
- FROM DAVIS (1925) "--- THAT THE FAULT PLANES ARE CURVED AND FLATTEN IN DEPTH, IF BORNE OUT BY FUTURE WORK, WOULD INDICATE THAT THE TILTING COULD HAVE BEEN CAUSED BY ROTATION OF THE BLOCKS ON SUCH CURVED PLANES; AND IT IS POSSIBLE THAT THE SHORTENING DUE TO TILTING MAY BE OF GREATER MAGNITUDE THAN THE EXTENSION RESULTING FROM NORMAL FAULTING."

FIGURE 8. Notes From Structural Geology of North America.

Demise of a Classic Concept

Ponder the COCORP 40-degree North Transect by Allmendinger (1987) and note the increasing recognition of the demise of the classic graben and horst concepts of the past century as they founder on mass balance, the laws of physics, and the revelation of the third-dimensional data that have remained proprietary for decades but are now becoming available (Figure 9).



FROM BULL. G.S.A. MARCH 1987

"NO ONE MODEL OF EXTENSION IS SUPPORTED BY THE SEISMIC DATA--- BUT ONLY THE MODEL OF SYMMETRIC HORSTS AND GRABENS CAN BE LARGELY RULED OUT"

FIGURE 9. Models of Extension From the Bulletin of the Geological Society of America.

We who study Coso are not just plunged into the exciting new debates over the very character of the Basin and Range, but we are intimate participants in the fundamental philosophic debates of the very origin of intrusive systems. We subscribe to mid-crustal melting, granitization if you like, with some co-located basaltic leakage of a sub-crustal origin for the main localized heat source at Coso. However, we also recognize the far greater greenschist metamorphic heat source of a regional extent that seems to be below the shallower intrusive system. See Figure 10.

THE ORIGIN OF THE GRANITIC MAGMA AT COSO

MID-CRUSTAL GRANITIZATION
VS
DIFFERENTIATION OF UNDERLYING BASALT

FROM GSA MEMOIR 28, "ORIGIN OF GRANITE" (1947)

- "THIS QUESTION OF THE ORIGIN OF GRANITE IS PERHAPS THE MOST LIVELY OF GEOLOGIC TOPICS TODAY - BUT WE SHOULD REMEMBER THAT IT ALWAYS HAS BEEN"

- "BIGOTS, OR IF YOU LIKE, ENTHUSIASTS, ON BOTH SIDES DO A DEAL OF HARM, AND PONTIFFS, I SUGGEST TO PROFESSOR BOWAN, WHILE CAPABLE OF A GREATER NUMBER OF GOOD DEEDS, ARE ALSO CAPABLE OF A GREATER NUMBER OF BAD DEEDS THAN THE VILLAGE DRUNK. IF WE KEEP OUR TEMPERS, WHILST NOT PULLING OUR PUNCHES, WE SHALL RECEIVE GREAT PROFIT AND PLEASURE FROM THESE DEBATES."

THE FOLLOWERS OF BOWEN (1915) VERSUS THE FOLLOWERS OF READ (1943) AND BARTH (1948)

FIGURE 10. The Origin of the Granitic Magma at Coso.

Thrusting, an Old But New-Found Concept

Our interpretation of the nature of the eastern margin of the Sierra Nevada is what many will consider a new concept. The classic view of the Sierra as a deep, some would say 85,000-foot deep, block of granitic rock bordered by an immense normal fault on its eastern margin founders on several problems. These problems include gravity, heat flow, geochemistry, isotope chemistry, and structure such as the anticlinal folding and faulting of adjacent valley-fill sediments with these anticlines and faults simply disappearing beneath the granitics. We believe that a sierran model based on thrusting is an attractive interpretation that answers many questions and is consistent with all that we know today. Figure 11 shows the three views of the Sierra Nevada-Coso area.

Little or no disagreement seems to exist at present that the margins of the continent are in compression. If the margins, why not the interior adjacent to the margins, i.e., the Great Valley and the Sierra Nevada province? See Figure 12.

THE NATURE OF THE SIERRA NEVADA - COSO AREA

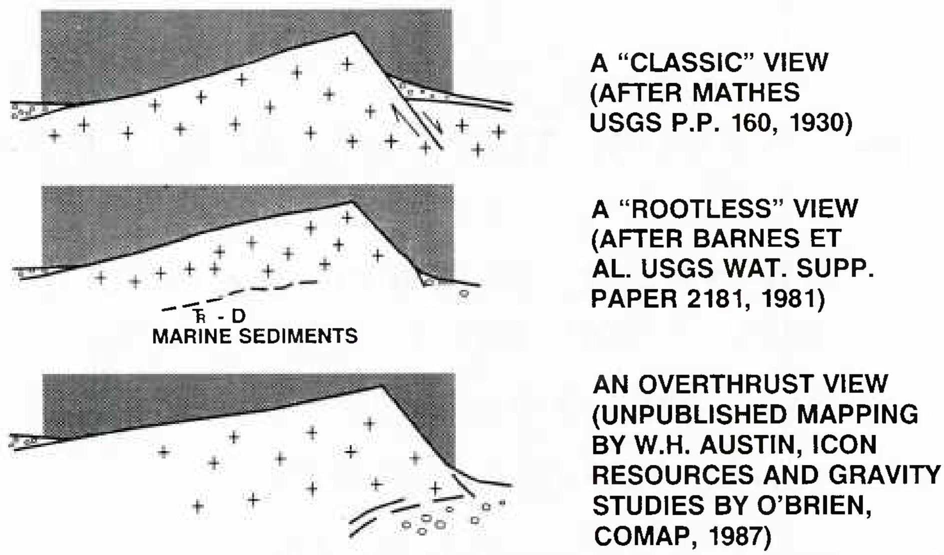


FIGURE 11. The Nature of the Sierra Nevada—Coso Area.

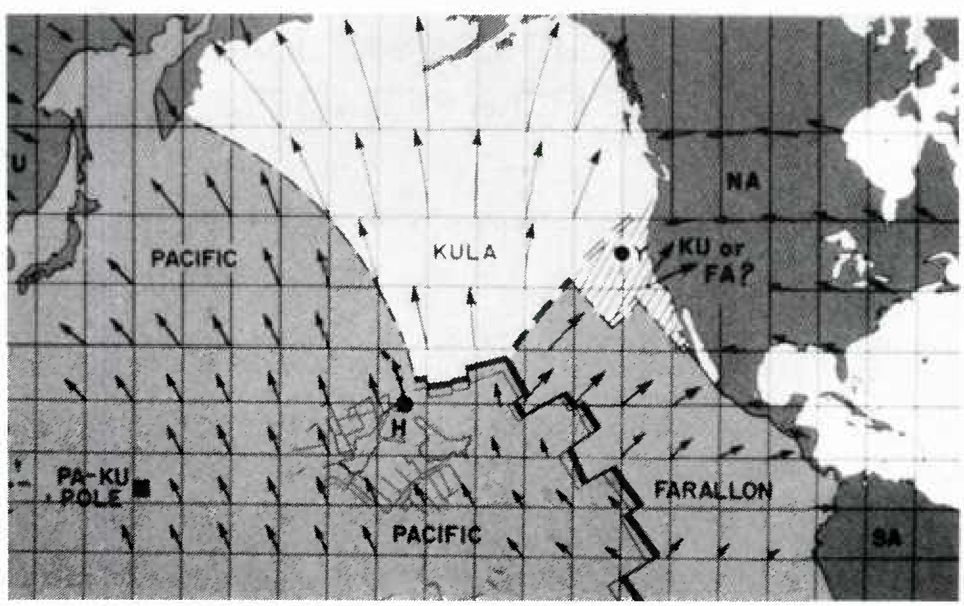


FIGURE 12. Configuration of Crustal Plates Under and Adjacent To North America.

The Compressional history of the southern Sierra Nevada and the adjoining areas on both sides of the Sierra, as outlined in Figure 13, is clear cut. Let us briefly look at these features: an intense Pliocene compressional overprint, episodes of warping, and some newly recognized thrusting in the San Joaquin Valley on the west side of the Sierra Nevada.

Baker (1913) began the debate over thrusting in the Basin and Range, and scientists such as Peter Misch (1960) of the University of Washington have continued to publish on overthrusting details. The theory of thrusting is increasingly with us today.

COMPRESSION OF THE COSO AREA - WHEN?

- BASIN AND RANGE (SOUTHERN) THE RESULT OF COMPRESSION - BAKER, J. GEOL. 1913
- LARAMIDE OVERPRINT - EARDLEY 1951
- PLIOCENE OVERPRINT - EARDLEY, 1951
- REPEATED WARPING AND PROFOUND MID-PLIOCENE OROGENY - HEWETT, 1954
- THRUSTING IN SOUTHERN SAN JOAQUIN VALLEY - UNPUBLISHED, EUREKA RESOURCES*

*Unpublished document, Eureka Resources, El Cerrito, Calif.

FIGURE 13. Compression of the Coso Area.

A typical proprietary study of the Basin and Range from a few years ago shows thrusting, a major thrust ramp, and extension on the surface in the form of thin tectonic denudation slices (Figure 14).

Coso is clearly within the Laramide zone of activity, being located essentially where Eardley (1951) would grade the Central Rockies into the Southern Arizona Rockies. We use Eardley's excellent text (Figure 15) to show that our ideas are not so much new as a reemphasis of existing problems and concepts that need to be reexamined in the light of extensive industrial and academic experience now becoming available to the geologic community.

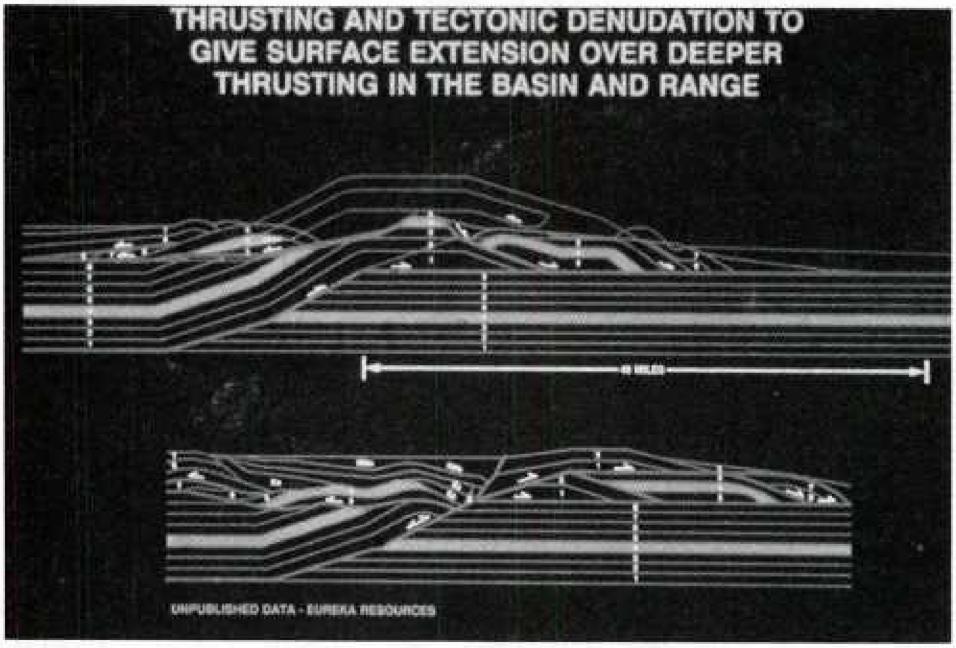


FIGURE 14. Thrusting and Tectonic Denudation To Give Surface Extension Over Deeper Thrusting in the Basin and Range.

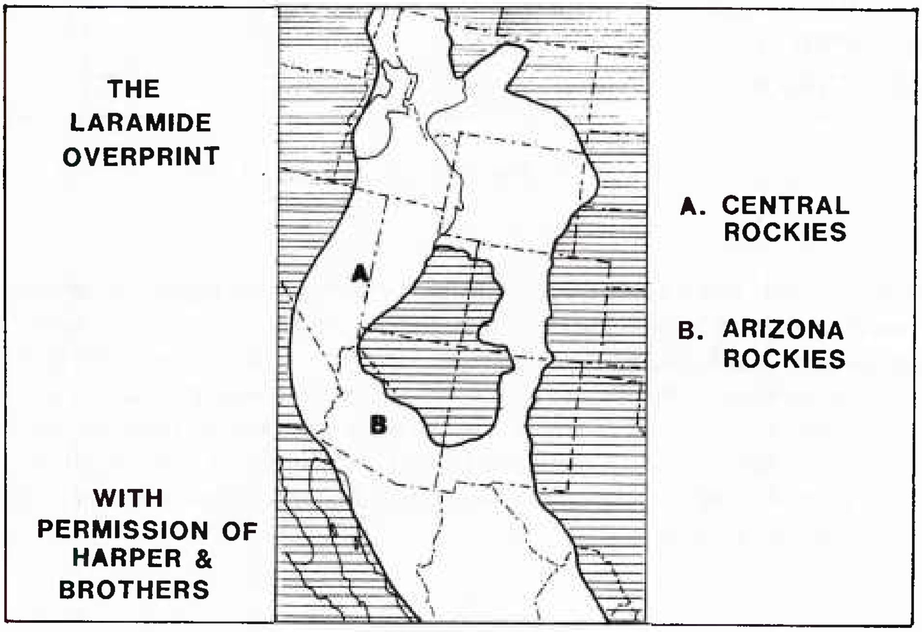


FIGURE 15. Map of the Laramide Overprint.

Of far greater local interest and certainly more timely in terms of new thrusting or rejuvenated motion on older thrusts, a zone of Pliocene thrusting is clearly called out by Eardley (1951) in Figure 16. We cannot help but note the obvious block Eardley showed on the south side of the Garlock Fault for which NASA scientists have recently described the rotational geometry. Coso is in that prominent zone of thrusting north of the Garlock Fault.

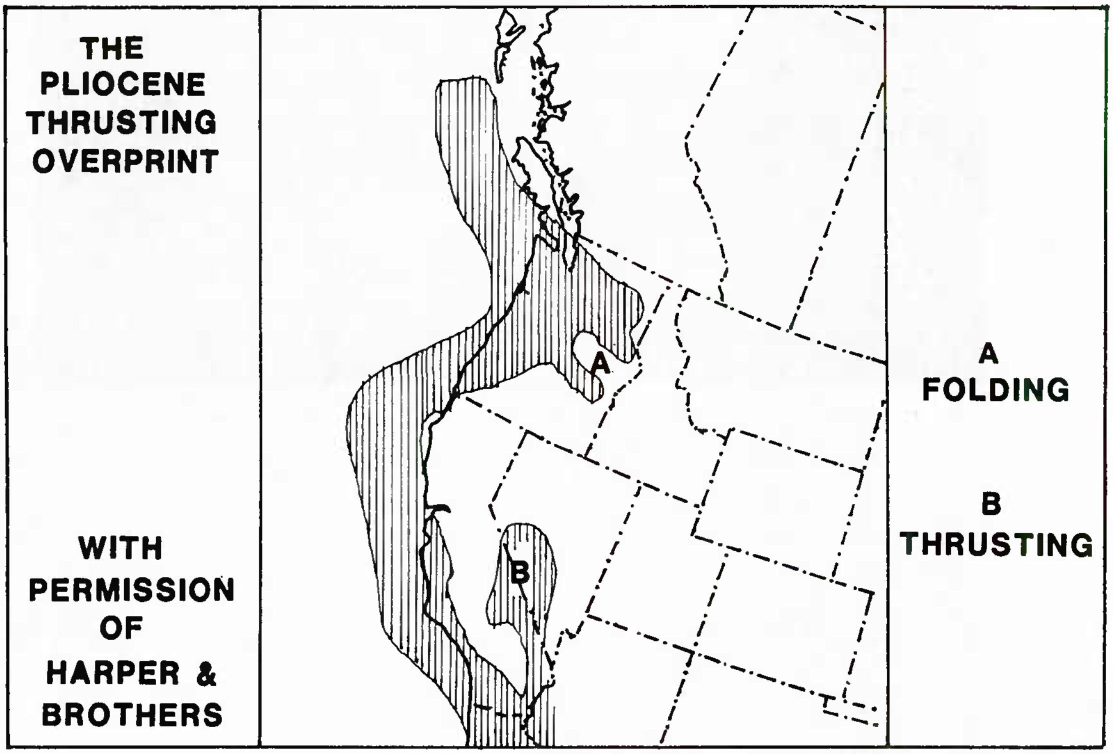


FIGURE 16. The Pliocene Thrusting Overprint.

Hewett (1954), in his chart of deformational events in this region, as shown in Figure 17, notes warping from mid-Miocene to the beginning of late Pleistocene, with, in his words, profound orogeny and folds and thrusts. At the end of mid-Pliocene, with the thrusting from this orogeny very evident in the Panamint Mountains, motion would most likely occur on older thrusts within this area as well, such as the extensive thrusting of uncertain age in the Darwin Hills, Talc City Hills, Argus Mountains, Coso Mountains, and adjacent Sierra. This motion would be primarily the result of compression, although relaxation slumping and tectonic denudation cannot be ignored.

DEFORMATION EVENTS APPLICABLE TO COSO REGION

FROM: D.F. HEWETT (U.S.G.S.) IN BULL. 170, CALIF DIV. MINES, 1954

RECENT		
PLEISTOCENE	LATE	NORMAL FAULTS
		LOCAL WARPING
	MID	WARPING
		LOCAL WARPING
	EARLY	
PLIOCENE	UP	PROFOUND OROGENY - FOLDS, THRUSTS
	MID	
	LOW	BROAD WARPS & LOCAL BASINS
MIOCENE	UP	
	MID	BROAD WARPS
	LOW	

FIGURE 17. Deformation Events Applicable to the Coso Region.

Briefly, we wish to call to your attention the increasing recognition of thrusting of a prominent nature in the oil fields of the San Joaquin Valley (Figure 18), showing that the Sierra Nevada has truly had the opportunity to be compressed and be faulted into a Basin- and Range-type structural feature.

THRUSTING IN SAN JOUAQUIN VALLEY

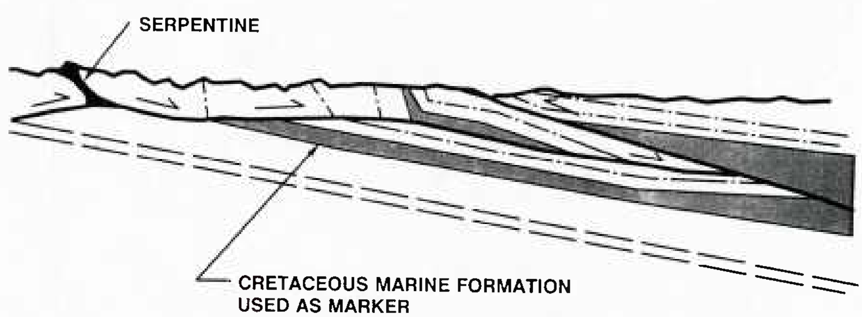


FIGURE 18. Thrusting in San Joaquin Valley.

Given thrusting in the region of Coso, is the vulcanism at Coso reflective of an offset heat source that is lost to the west under the Sierra, or is the heat source still located below Coso? This question is vital in evaluating the size and longevity of the geothermal field. Figure 19 shows features ranging from the subdued wreckage of an older perlite dome to domes too young for ordinary dating procedures closely spaced with one another. This juxtaposition indicates a heat source active below, or at least a heat source feeding into a localized relatively shallow zone.

This cross section, shown in Figure 23, prepared by Fournier and Thompson (1980) shows both recharge patterns for the Coso reservoir and the importance of the pervasive fracturing and breakup of the thin thrust sheet of sierran granitics. This process of thrusting and breakup provides the massive permeability in the Sierran recharge zones as well as in the reservoir itself and enables the shallow portion (upper 2 miles) of the Coso wells to be so highly productive.

FIGURE 19. How Old the Vulcanism.

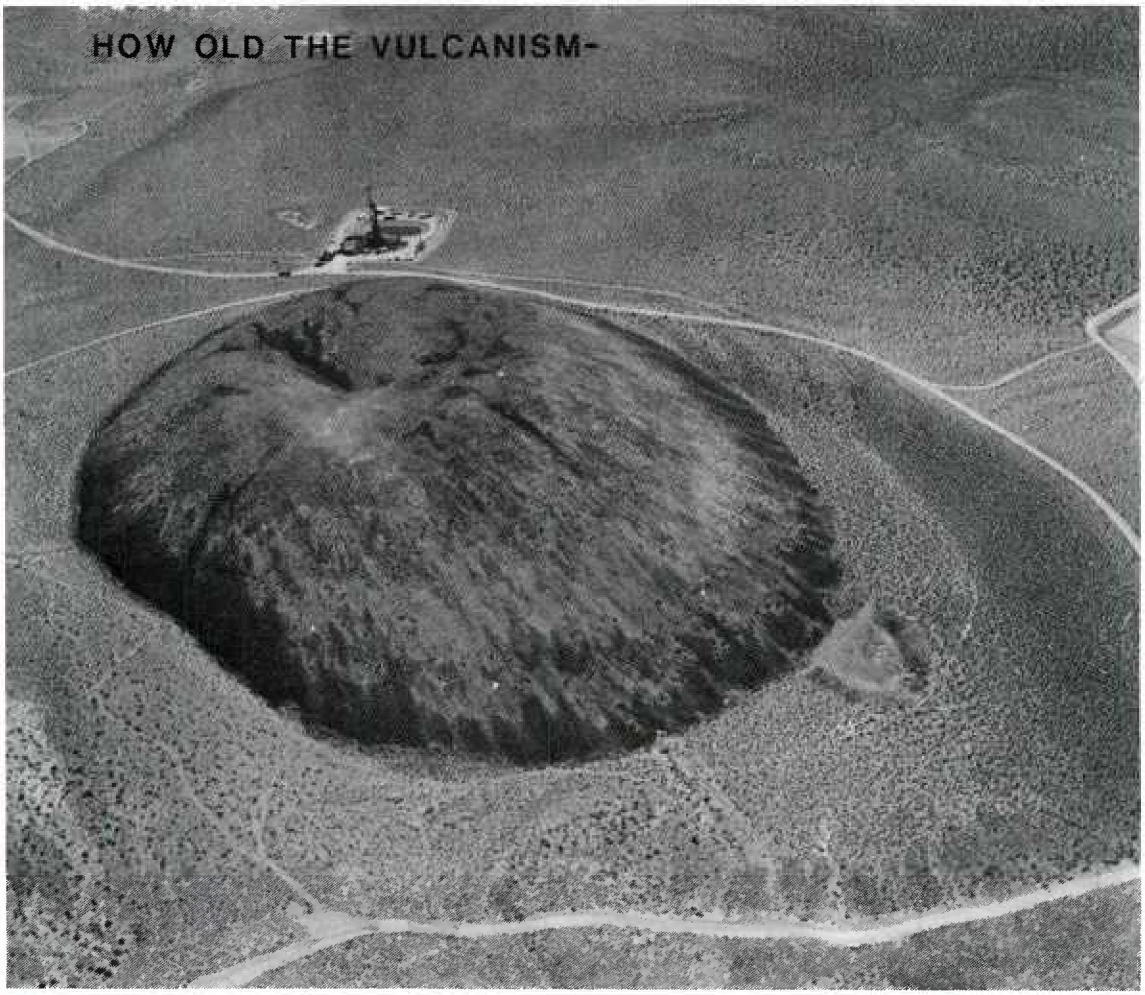


FIGURE 20. Young Volcanic Feature.

Fractures as Critical Elements

To compound our problem of structural interpretation, recent mapping in Coso shows a problem faced by anyone mapping or using maps: the question of which fractures to show and which to ignore. We believe that the map shown in Figure 21 obviously reflected Roquemore's (1982) bias toward a model of east-west extension for Coso. Yet the person planning a drilling campaign does not drill regional models, but drills along actual fracture patterns if the intent is to be a sharpshooter as opposed to relying on a scatter-gun drilling effort. In the evaluation of the actual structure present at Coso, one cannot blandly ignore the fracture pattern so clearly shown by linear arrays of perlite domes. These fractures and their intersections are critical elements of the reservoir and critical drilling targets, whether covered by veneers of volcanic debris, and whether or not they fit some popular regional model of the geology.

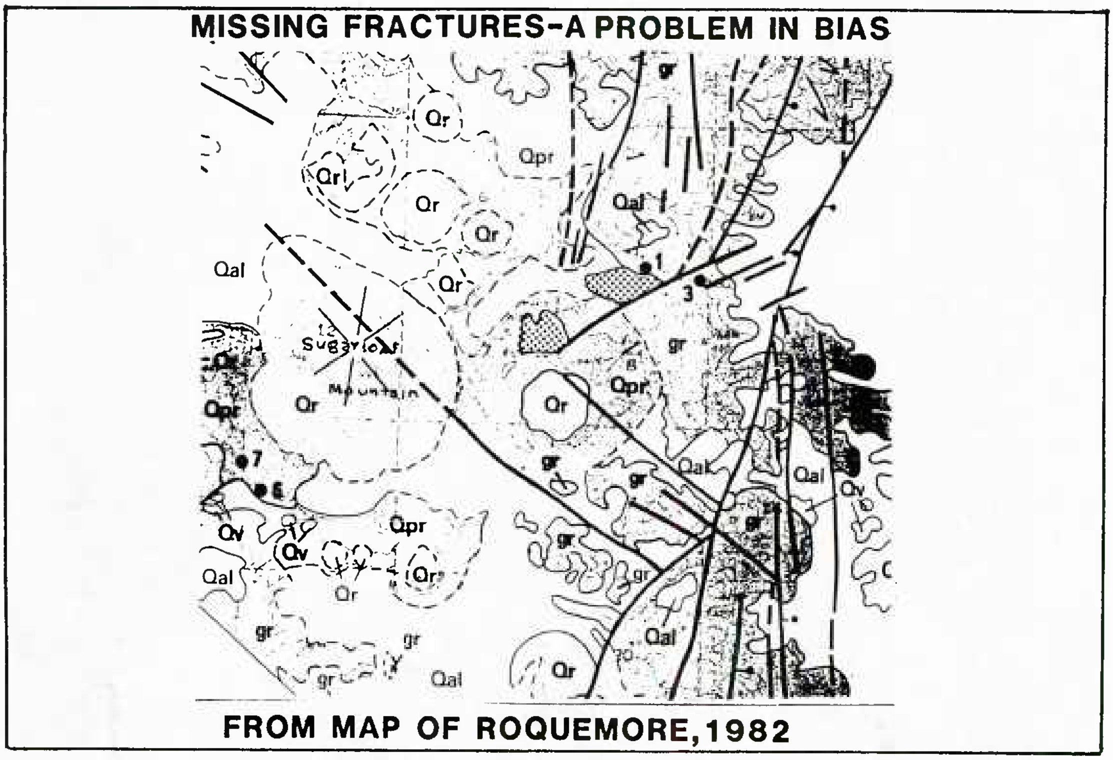


FIGURE 21. Missing Fractures—A Problem in Bias.

The cartoon in Figure 22 showns in general terms the actual drilling targets being sought at Coso:

1. Vertical breccia pipes or zones, both volcanic and hydrothermal in origin, the most productive zones to date
2. Fracture intersection breccias
3. Linear breccia zones
4. Spreading fracture networks, the least productive to date but of great value as injection sites

This cross section, shown in Figure 23, prepared by Fournier and Thompson (1980) shows both recharge patterns for the Coso reservoir and the importance of the pervasive fracturing and breakup of the thin thrust sheet of sierran granitics. This process of thrusting and breakup provides the massive permeability in the sierran recharge zones as well as in the reservoir itself and enables the shallow portion (upper 2 miles) of the Coso wells to be so highly productive.

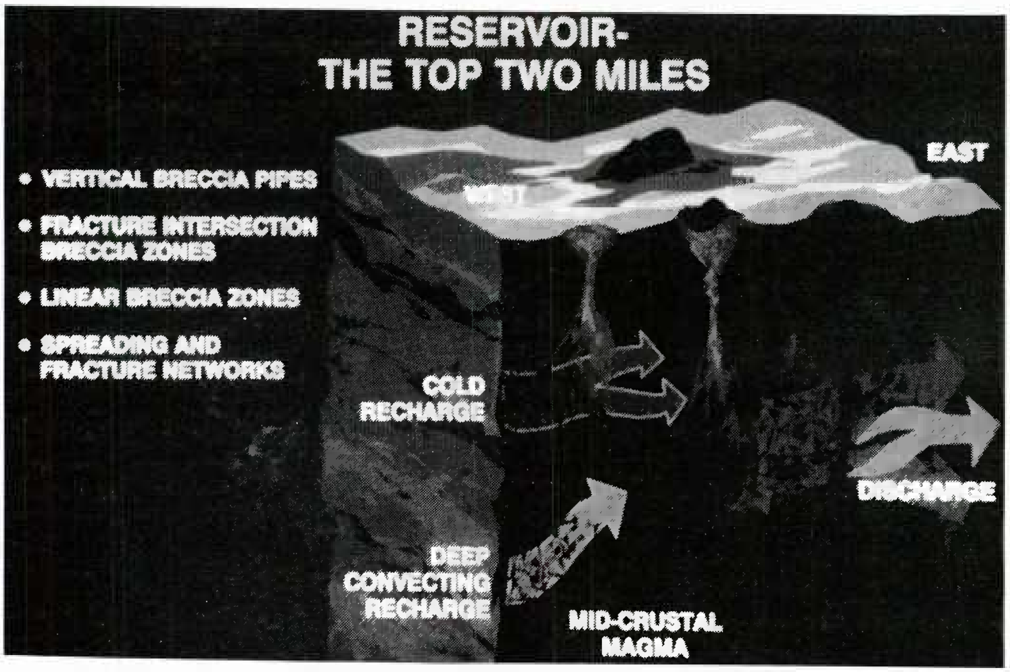


FIGURE 22. Coso Drilling Targets.

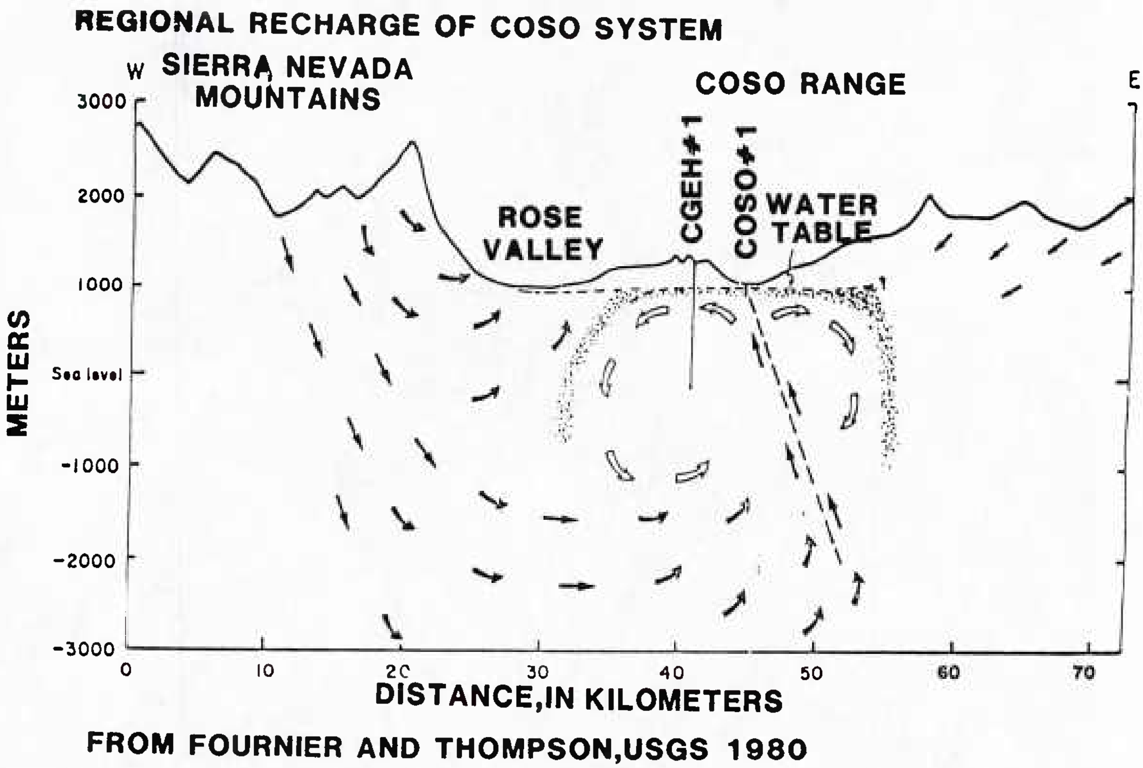


FIGURE 23. Recharge Patterns of the Coso System.

The model selected for the Coso geothermal field must account for the following features:

1. The 20-mile-diameter arcuate fracture pattern
2. The north-south fractures cresting the folded granitics of the central ridge
3. The prominent north-west fractures that offset the sierran granitics
4. The radial fractures within the Coso geothermal field
5. The geochemistry of the steam wells and carbonate mounds of the area
6. The over-thrusting seen in adjacent valleys and ranges

Examples of these features follow.

Arcuate fracturing with a 65-degree inward dip that forms the northern quadrant of the Coso arcuate fracture zone is shown in Figure 24.

Figure 25 shows north-south extensional fracturing mapped by Roquemore (1982) and marking the crest of the main fold of the thrust sheet of Coso and the adjacent fold over the thrust-ramp zone of the Argus range to the east.

FIGURE 24. Arcuate Fracturing of Northern Coso Arcuate Fracture Zone.

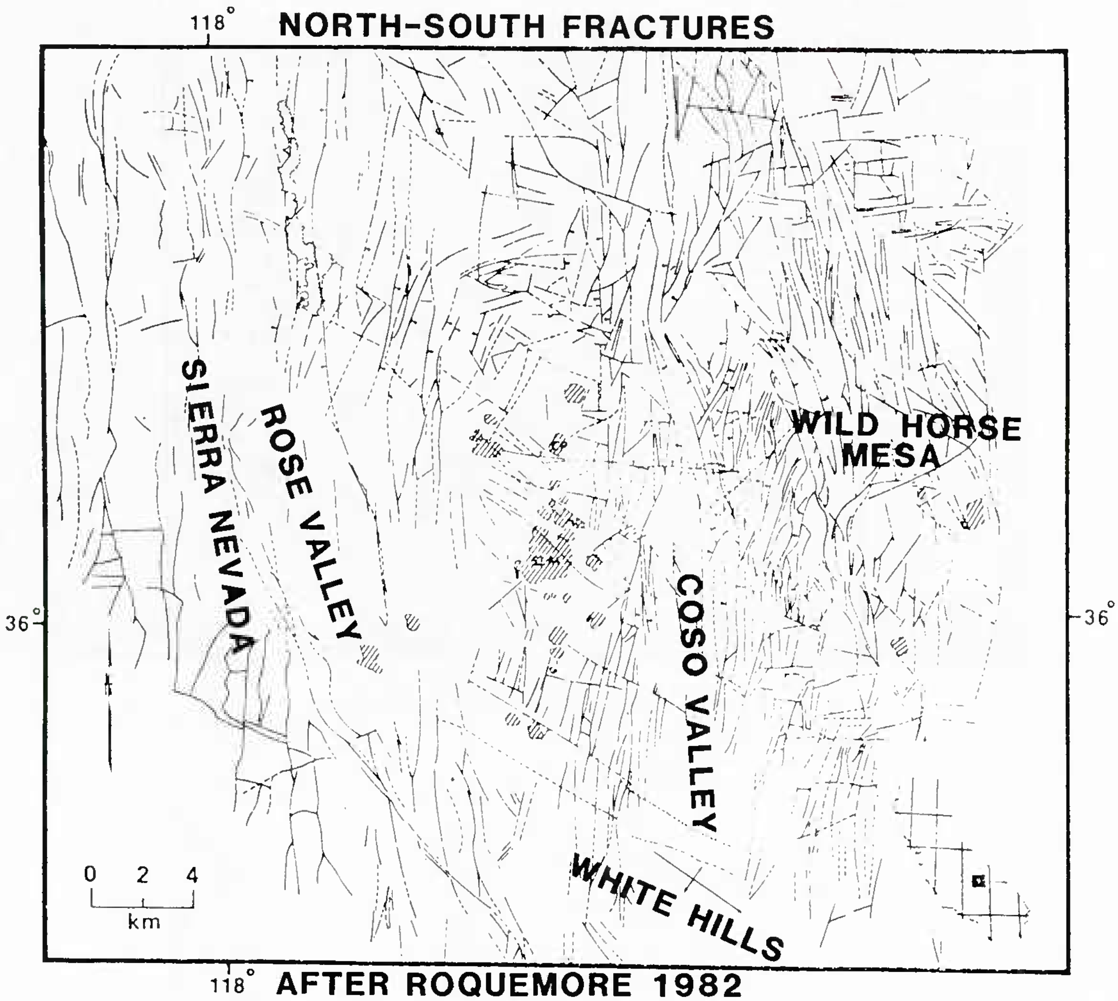


FIGURE 25. North-South Extensional Fracturing.

Figure 26 shows north-west trending fractures, apparently complements to the Garlock's main motion. These fractures are shown by drag folding on the Garlock Fault itself, offsetting the Sierra by some 7800 feet at Little Lake and nearly 1400 feet at No Name Canyon.

Figure 27 shows the radial fractures noted by Austin and Durbin (1985) in their study of the Coso Reservoir. The perlite dome rows are not parallel, but converge, and one can interpret these radial fractures as the result of hoop stresses around four nodal points that can best be considered zones of forcible intrusion at shallow depths.

The carbonate mounds of the southern and central Sierra (Figure 28), studied by Barnes and others (1981), are not unique to the Sierra. We have large mounds in the Argus, some in the Cosos, and carbonate leakage in the eastern-most Sierra that are strongly suggestive of marine sediments below the granitic surface.

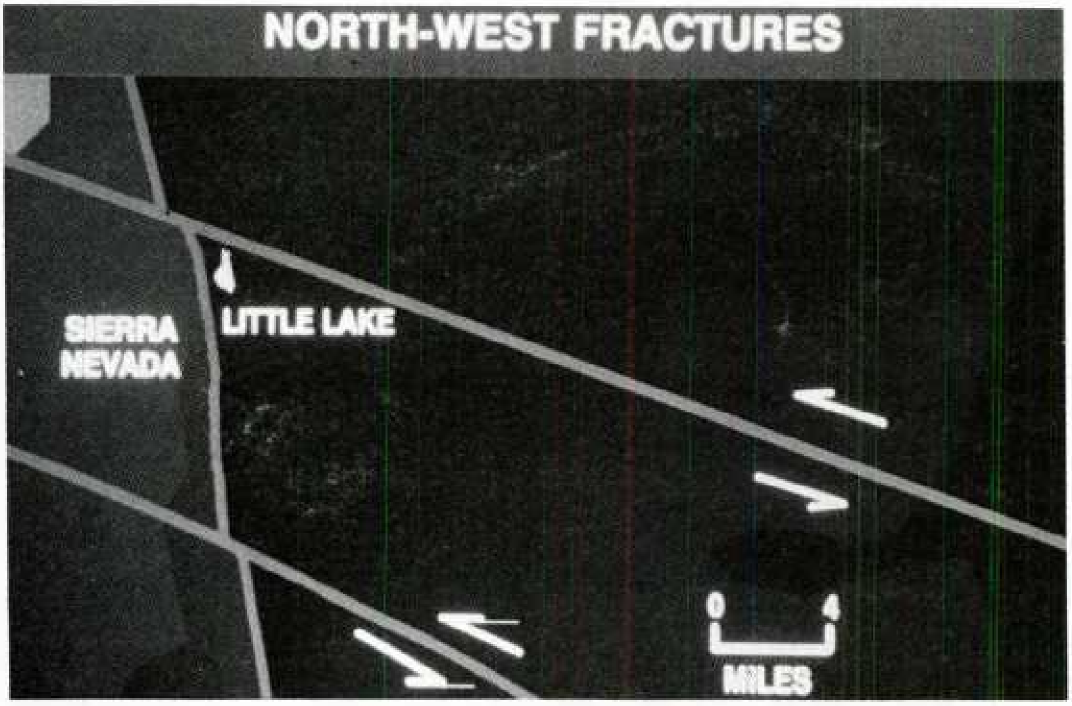


FIGURE 26. North-West Fractures.

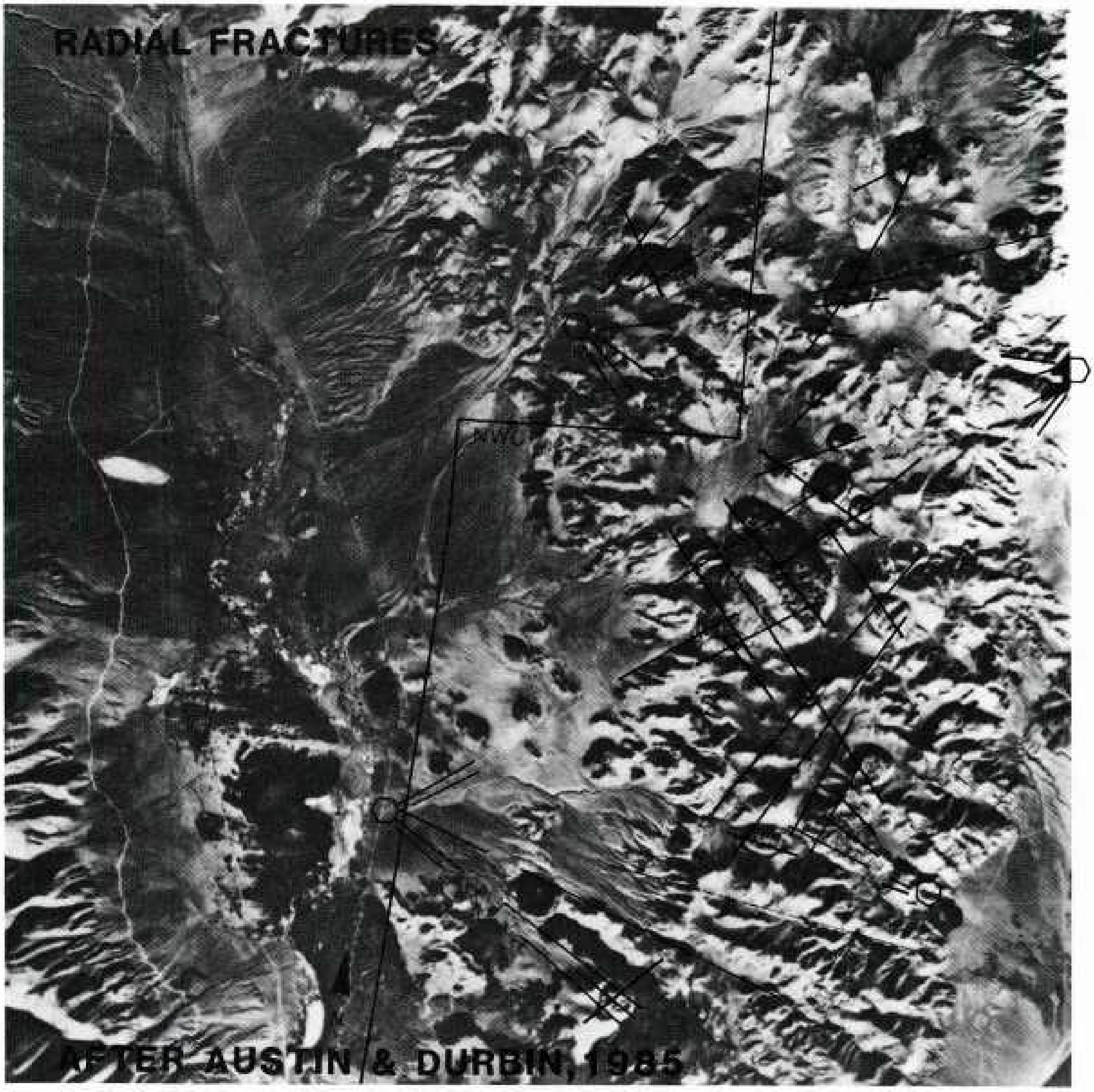


FIGURE 27. Radial Fractures.

FIGURE 28. Typical Carbonate Mound.

Mapping by Ward Austin (1987) of Icon Resources, Ltd., Lakewood, Colo. (Figure 29), and detailed gravity interpretation by O'Brien of Comap Exploration Services, Inc., Lakewood, Colo., show the Indian Wells Valley south of Coso to be overthrust by at least 7 kilometers. In effect, 7 kilometers of granite have moved out over the valley fill. Not only has Silver (1986) of CalTech found and published on stacked low-angle faults in the Sierra just south of Indian Wells Valley, but the air-photo and gravity data are powerfully supportive of thrusting along much of the southern Sierra front if not along all of it, including the portion adjacent to Coso.

Modeling of the Coso Area

We are realists enough to recognize that our interpretations are going to excite great controversy among traditionalists, and many more generations will be required to resolve the mechanics of Basin and Range Fault formation, not to mention the debates over the origins of granite. Figure 30 shows a concept held by the proponents of classic geological theories.

Our exploration model for Coso shows the Sierra thrust eastward as an "exotic" terrain of a rootless nature, riding with and over marine sediments (Figure 31). The folded granites of the central ridge are the "rolled over" leading edge of a thrust sheet, and the active intrusive below is tucked into the underlying thrust ramp of the Argus Mountains. Motion on the Coso system of thrusting postdates one perlite dome, one we believe now to be a rootless dome aged one million years.

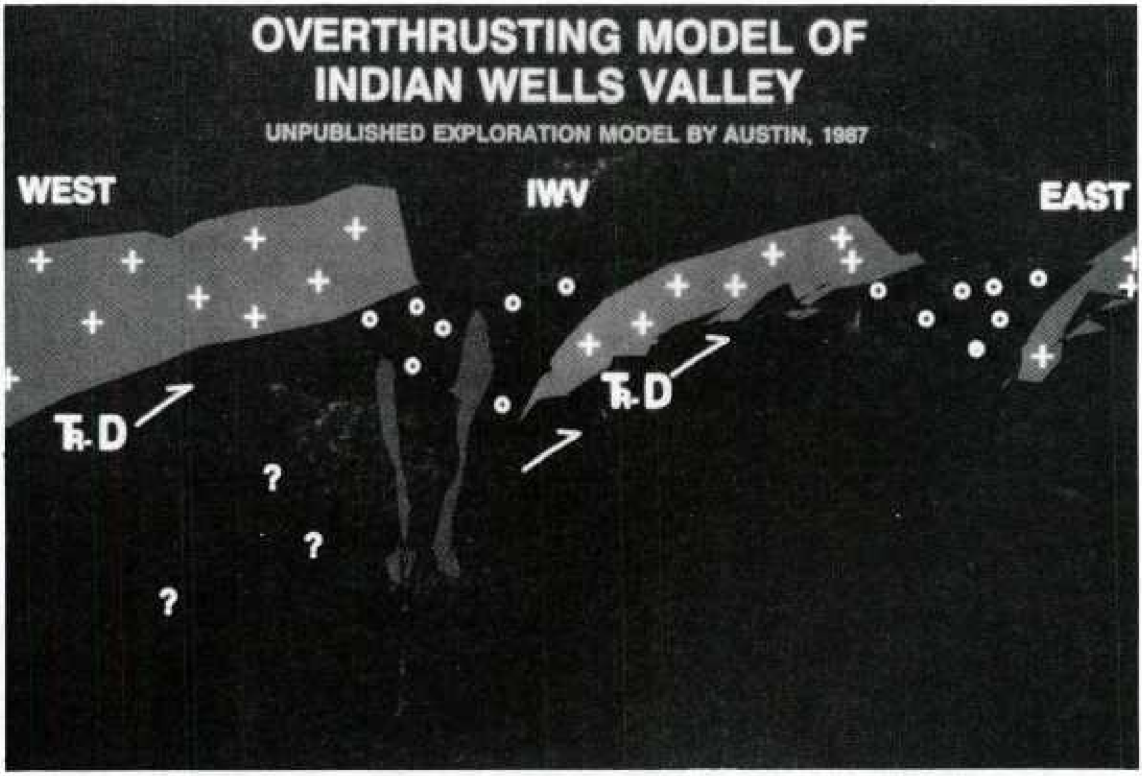


FIGURE 29. Overthrusting Model of Indian Wells Valley.

THE PROPONENTS OF CLASSIC THEORIES SEEK REFUGE IN THE FOLLOWING CONCEPT

"THE BROAD PICTURE OFTEN CAN ELUDE THE GEOLOGIST PRESENTED WITH AN ABUNDANCE OF WELL EXPOSED DETAIL"

QUOTE OF NORRIS AND WEBB, " GEOLOGY OF CALIFORNIA" IN RELATION TO MID-PLIOCENE THRUSTING IN BASIN AND RANGE EAST AND SOUTH OF COSO REGION

FIGURE 30. Concept of Classic Theorists.

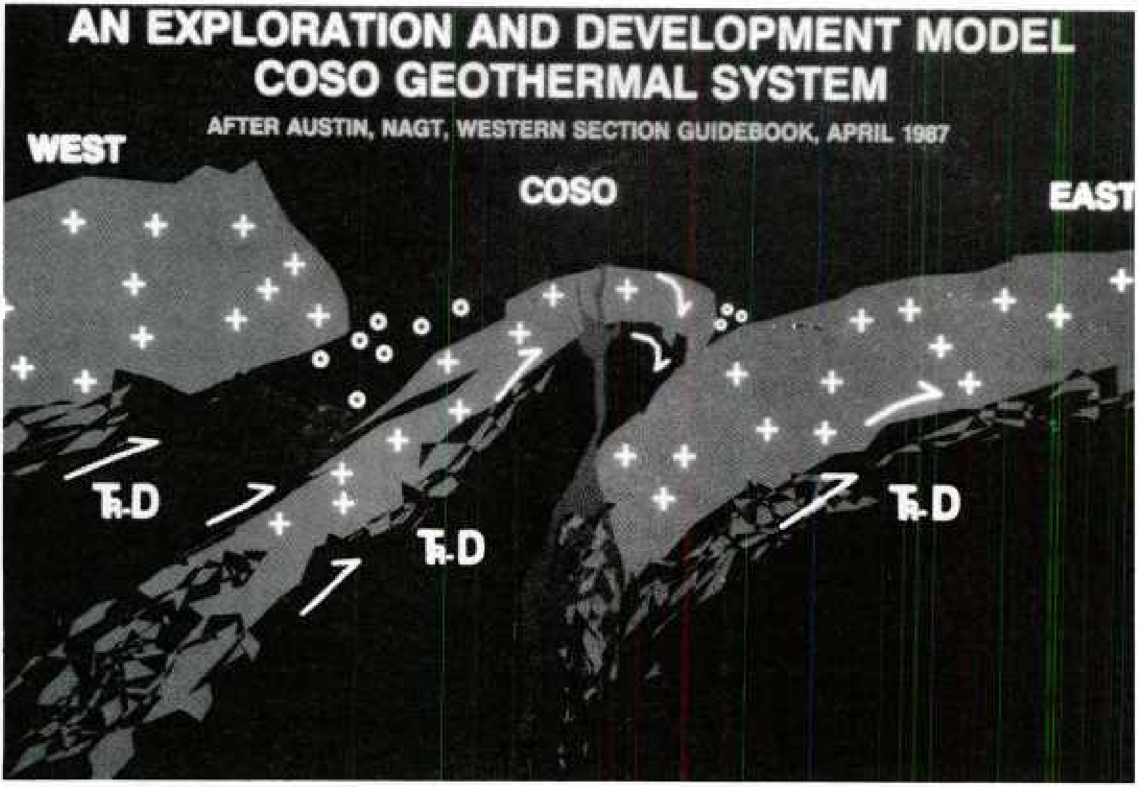


FIGURE 31. An Exploration and Development Model of the Coso Geothermal System.

You will note on our model a proposed small accumulation of magma at a depth of about 11,000 feet. The presence of this magma is supported by seismic and thermal-gradient data, and we believe that it marks the base of the granitic portion of the shallow reservoir that we are developing at Coso. We propose that the marine sediments believed to underlie the Sierra are beneath Coso (and the Argus Range too) and that this marine sediment layer is the source of both the hydrocarbons in the steam at Coso and the increasing chloride at depth.

Economic Implications

The economic implications of our structural model for Coso and the southern Sierra Nevada as shown in Figure 32 are exciting. Obviously, we can neither prove nor disprove our model at this stage, but we would point out that neither popular dogma nor controversy has any probative

ECONOMIC IMPLICATIONS OF OVERTHRUST MODEL OF SOUTHERN SIERRA AND ADJACENT RANGES

- **GROUNDWATER FLOW PATTERNS**
- **SALINES UNDER THIN OVERTHRUSTS**
- **GEOTHERMAL DEPOSITS COVERED BY GRANITIC VENEER**
- **HIDDEN EPITHERMAL PRECIOUS METAL ZONES**
- **MARINE-SEDIMENTS MAY UNDERLIE WEST SLOPE OF SIERRA AT DRILLABLE DEPTHS COULD BE MAJOR OIL AND GAS TARGET**

FIGURE 32. Economic Implications of Overthrust Model of Southern Sierra and Adjacent Ranges.

value. Rather, the market place will be our real judge. If the model we show for the southern Sierra Nevada is believable to the exploration community, then the following economic corollaries exist for testing by industry and municipalities:

1. Groundwater. The potential exists for major subsurface groundwater recharge downward through the sierran thrust sheet into the underlying valley-fill sediments overridden by the thrusting. The potential exists in some valleys for major water loss as well, into valleys to the east. Potentially significant additional groundwater storage in overridden valley fill in the valleys adjacent to the Sierra has been unrecognized to date.

2. Saline Minerals. The potential exists for saline mineral deposits in Searles Valley. These deposits may extend to the west under the thin granitic veneer of the Argus Range and the Spangler Hills. The possibility also exist that such deposits occur in overridden portions of Panamint Valley.

3. Geothermal Deposits. In Indian Wells Valley, unpublished studies show groundwater that is clearly a steam condensate. These studies also show zones of groundwater with a silica content of over 70 parts per million (PPM). These waters give the strong appearance of being leakage from beneath the sierran granitics, and gravity data suggest that an intrusive just to the west, beneath the thrust sheet, is the source of these fluids. This intrusive and other hidden geothermals appear highly possible in the region.

4. Precious Metal Ores. All 14 of the geothermal prospects that we showed for the Coso region have the potential for associated epithermal ore deposits. Several of these areas are at or near pervasive zones of hydrothermal alternation. Conceivably, pulses of mineralization may be represented by both discrete zones or elongated zones in overlying thin thrust sheets or as linear boiling-zone type deposits just behind the leading edges of thrusts.

5. Oil and Gas. If indeed the sierran granitics are not only rootless but overlay marine sediments, then as one goes westward away from the intrusive centers associated with the underlying thrust-ramp geometry, the conditions may favor oil and gas accumulation in and beneath the granitic veneer. Thus, the western foothills of the Sierra Nevada and the eastern edge of the San Joaquin Valley may contain major petroleum reserves. We think that the time has come to find out.

REFERENCES

Allmendinger, R.W., and others. 1987. "Overview of the COCORP 40° N Transect, Western United States: The Fabric of an Orogenic Belt," *Geological Society of America Bulletin,* Vol. 98, No. 3, pp. 308-19.

Austin, Carl F., and William F. Durbin, 1985. *Coso: Example of a Complex Geothermal Reservoir.* China Lake, Calif., Naval Weapons Center, September 1985. 96 pp. (NWC TP 6658, publication UNCLASSIFIED.)

Austin, Carl F. April 1987. "The Coso Geothermal System, " in *Geological Excursions Through Southern Owens Valley,* presented at the National Association of Geology Teachers Far Western Section Spring Meeting.

Austin, Ward H. 1987. *Preliminary Report on the Orthophoto Fault/Fracture Analysis of the Indian Wells Valley Area.* Icon Resources Ltd. (Unpublished report can be obtained from East Kern County Resource Conservation District, Inyokern, CA 93527.)

Baker, C.L. 1913. "The Nature of the Later Deformation in Certain Ranges of the Great Basin," Journal of Geology, Vol. 21, pp. 273-78.

Barnes, Ivan and others. 1981. *Geochemical Evidence on the Nature of the Basement Rocks of the Sierra Nevada, California.* USGS Water-Supply Paper 2181.

Davis, W.M. 1925. "The Basin Range Problem," in Proc. *National Academy of Science U.S.*, Vol. 11, pp. 387-92.

Eardley, A.J. 1951. *Structural Geology of North America.* New York, Harper & Brothers.

Fournier, R.O. and J.M. Thompson. 1980. *The Recharge Area for the Coso, California Geothermal System, Deduced from δD and δ180 in Thermal and Non-Thermal Waters in the Region.* U.S. Geological Survey. Open-File Report 80-454, 25 pp.

Gilbert, G.K. 1874. *U.S. Geographical and Geological Surveys W. 100th Mer. Progress Report,* 1872.

Hewett, D.F. 1954. "General Geology of the Mojave Desert Region, California," *Geology of Southern California.* California Division of Mines, San Francisco. Bulletin 170, Vol. 1, pp. 5-20.

King, Clarence. *Mountaineering in the Sierra Nevada.* University of Nebraska Press, Lincoln, Neb.

Lageson, David R. 1982. *Regional Tectonics of the Cordilleran Fold and Thrust Belt.* Montana State University, Dept. of Earth Sciences, Bozeman, Mont.

Lawson, A.C. 1936. "The Sierra Nevada in the Light of Isostasy," *Geol. Soc. Am. Bull.*, Vol. 47, pp. 1691-1712.

Mayo, E.B. 1941. "Deformation in the Interval Mt. Lyell-Mt. Whitney, California," *Geol. Soc. Am. Bull.*, Vol. 52, pp. 1001-84.

Misch, Peter. 1960. "Regional Structural Reconnaissance in Central-Northeast Nevada and Some Adjacent Areas: Observations and Interpretations" in *Geology of East Central Nevada, Intermountain Association of Petroleum Geologists, 11th Annual Field Conference-Guidebook,* ed. by J. Boetther and W.J. Sloan. 1960. Pp. 17-42.

Nolan, 1943. "The Basin and Range Province in Utah, Nevada, and California," *U.S. Geological Survey Professional Paper 197-D,* pp. 141-96.

O'Brien, Douglas P. 1987. *Compilation and Interpretation of Gravity and Magnetic Data in the Indian Wells Valley Area, Including Portions of Bakersfield and Trona 1:250,000 Quadrangles California.* Lakewood, Colo., Comap Exploration Services, Inc. Unpublished report prepared for Ward H. Austin, Icon Resources, Ltd.

Read, H.H. 1947. "Granites and Granites" in *Geological Society of America Memoir 28, on Origin of Granite,* ed. by James Gilluly. Geological Society of American Conference, 30 December 1947, document published 10 April 1948.

Roquemore, Glenn R. 1982. *Reconnaissance Geology and Structure of the Coso Range, California.* China Lake, Calif., Naval Weapons Center, May 1982. 26 pp. (NWC TP 6036, publication UNCLASSIFIED.)

Silver, Leon T. 1986. *Evidence for Paleogene Low-Angle Detachment of the Southern Sierra Nevada.* Pasadena, Calif., Division of Geological and Planetary Sciences, California Institute of Technology.

Spurr, J.E. 1901. "Origin and Structure of the Basin Ranges," *Geol. Soc. Am. Bull.*, Vol. 12, pp. 217-70.

Willis, Bailey. 1934. *National Research Council, Division of Geology and Geography, Annual Report.* 1933-34, App. I, pp. 12-13.

INITIAL DISTRIBUTION

2 Naval Air Systems Command (AIR-5004)
2 Chief of Naval Operations
  OP-413F (1)
  OP-45 (1)
2 Chief of Naval Research, Arlington (OCNR-1
8 Naval Facilities Engineering Command, Al
  FAC-03 (1)
  FAC-032E (1)
  FAC-04 (1)
  FAC-08T (1)
  FAC-09B (1)
  FAC-111 (1)
  FAC-111B (1)
  FAC-1113 (1)
1 Naval Facilities Engineering Comman tlan Divi
1 Naval Facilities Engineering Comma orther ilities
1 Naval Facilities Engineering Comm acific Di rbor (Utilities Divis
1 Naval Facilities Engineering Comm uthern Di ston (Utilities Divisio
5 Naval Facilities Engineering Com estern Divisi uno
  Code 09B (1)
  Code 09C3 (1)
  Code 11 (1)
  Code 1112 (1)
  Code 24 (1)
4 Naval Sea Systems Command
  SEA-05H7 (1)
  SEA-070C (1)
  SEA-09B312 (2)
3 Space and Naval Warfare Systems Command
  SPAWAR-00 (2)
  SPAWAR-005 (1)
1 Commander in Chief, U.S. Pacific Fleet, Pearl Harbor (Code 325)
1 Headquarters, U.S. Marine Corps (LFF-2)
1 Commander, Third Fleet, Pearl Harbor
1 Commander, Seventh Fleet, San Francisco
3 Naval Academy, Annapolis
  Director of Research (2)
  Library (1)
5 Naval Civil Engineering Laboratory, Port Hueneme
  Commanding Officer (1)
  L70 (1)
  L70PM (1)
  L72, D. Holmes (1)
  Technical Library (1)
2 Naval Energy & Environmental Support Activity, Port Hueneme
  Code 1101 (1)
  Code 111A (1)

1 Naval Postgraduate School, Monterey (Library)
1 Naval War College, Newport
1 Navy Energy and Natural Resources Research and Development Office
1 Chief of Engineers (DAEN-RDM)
1 Headquarters, U.S. Air Force (AF/LEYSF)
2 Air Force Academy, Colorado Springs
    Code LGSF (1)
    Library (1)
1 Air Force Intelligence Service, Bolling Air Force Base (AFIS/INTAW, MAJ R. Lecklider)
1 Civil Engineering Center, Tyndall Air Force Base (DEB)
12 Defense Technical Information Center, Alexandria
1 Department of Energy, San Francisco Operations, Oakland, CA (J. Crawford)
1 United States Geological Survey, Menlo Park, CA (Library)
1 Associated Universities, Inc., Upton, NY (Brookhaven National Laboratory)
2 California Energy Company, Incorporated, Santa Rosa, CA
    A. K. Carter, Administrative Manager, Comliance (1)
    J.L. Moore, Vice President, Exploration (1)
1 Lawrence Berkeley Laboratory, Berkeley, CA
1 Los Alamos National Laboratory, Los Alamos, NM (Reports Library)
1 Oak Ridge National Laboratory, Oak Ridge, TN (Energy Division)
1 The Johns Hopkins University, Applied Physics Laboratory, Laurel, MD
1 University of Utah, Salt Lake City, UT (Department of Geology, Dr. J. A. Whelan)
1 University of Utah Research Institute, Salt Lake City, UT (Earth Sciences Group)